

Development of a kinetic model for bainitic isothermal transformation in transformation-induced plasticity steels

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Abstract

In this work, we modify existing models to simulate the kinetics of bainitic transformation during the bainitic isothermal transformation (BIT) stage of a typical two-stage heat treatment – BIT is preceded by an intercritical annealing treatment – for TRIP steels. This effort is motivated by experiments performed in a conventional TRIP steel alloy (Fe–0.32C–1.42Mn–1.56Si) that suggest that thermodynamics alone are not sufficient to predict the amount of retained austenite after BIT. The model implemented in this work considers the non-homogeneous distribution of carbon – resulting from finite carbon diffusion rates – within the retained austenite during bainitic transformation. This non-homogeneous distribution is responsible for average austenite carbon enrichments beyond the so-called T_0 line, the temperature at which the chemical driving force for the bainitic transformation is exhausted. In order to attain good agreement with experiments, the existence of carbon-rich austenite films adjacent to bainitic ferrite plates is posited. The presence of this austenite film is motivated by earlier experimental work published by other groups in the past decade. The model is compared with experimental results and good qualitative agreement is found.

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1. Introduction

1.1. TRIP-assisted steels

Low-alloy, high-ductility transformation-induced plasticity (TRIP)-assisted steels constitute a possible cost-effective strategy for vehicle weight reduction, which in turn can significantly improve the fuel economy of the vehicle fleet. Many works have shown TRIP-assisted steels to have outstanding mechanical performance compared to other low-cost steel alloys [1–3]. TRIP-assisted steels (with Fe–C–Mn–Si as their main constituents) have a multi-phase microstructure consisting of ferrite, bainite and martensite as well as finite amounts of retained austenite (RA). In fact, one of the key characteristics of these low-alloy steels is the presence of the stabilized (retained) austenite phase, which

contributes to the enhancement of the overall ductility through its martensitic transformation during deformation. Since carbon is a very efficient austenite stabilizer, carbon enrichment of RA (w_C^{γ}) is an effective way to control the stability of austenite while keeping the amounts of other alloying elements at a minimum. With respect to the other phases, the proper control of w_C^{γ} can improve the mechanical properties – especially elongation [3–5] – of these steels. In addition to the control of the stability of RA, optimal design of multi-phase TRIP steels requires the accurate control of the volume fraction (and microstructural features) of the different constituent phases (ferrite, bainite and martensite). This can in turn be achieved through the careful design of appropriate heat treatments.

1.2. Two-stage heat treatment

Although there are many possible treatment strategies to maximize the stability of the RA, as well as to control the

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amount of other phases necessary to optimize the mechanical response of TRIP-assisted steels, the most common approach is a heat treatment that consists of two stages [6,7,4]: first, an isothermal hold within the ferrite + austenite two-phase field (intercritical annealing, IA), followed by a rapid quench to a lower temperature at which the IA-austenite (partially) transforms isothermally into bainite (bainitic isothermal treatment, BIT), as shown in Fig. 1.

During IA, the initial pearlitic microstructure is dissolved, which results in a two-phase microstructure consisting of austenite and ferrite. The microstructural change during IA has two main functions: first, the formation of ferrite contributes to the overall ductility of the alloy; second, the partitioning of carbon from IA-ferrite to IA-austenite (ferrite has almost no C solubility) stabilizes the latter against martensitic transformation upon quenching to lower temperatures. After IA, the alloy is quenched and held at a lower temperature (T_{BIT}) to induce the (partial) isothermal transformation of IA-austenite into bainite. The formation of almost C-free bainitic ferrite results in carbon rejection into the remaining austenite – provided carbide formation is suppressed or retarded – which contributes to the further stabilization of austenite upon quenching to room temperature. This is a necessary condition in order to take advantage of the TRIP effect and the enhanced ductility it provides.

Due to the importance of the BIT treatment in dictating the carbon enrichment in austenite, considerable effort has been dedicated to the understanding of the thermodynamics and kinetics of this important phase transformation [8–11]. Although there are still many aspects of the transformation subject to debate, the incomplete nature of bainitic transformation in many alloys over broad temperature ranges is a phenomenon that has been widely observed by many groups for a long time, so this phenomenon can be considered as given. On the other hand, the physical reason for the interruption of this phase transformation is still a controversial matter.

Recently, Aaronson and collaborators [11] examined different theories as well as experimental data, and concluded that a possible explanation for the incomplete nature of the BIT reaction involves the cessation of growth

due to a coupled-solute drag effect accentuated by overlapping carbon diffusion fields associated with nearby ferrite crystals [11]. On the other hand, Bhadeshia and collaborators [12,13] explained the incomplete nature of the BIT reaction as a consequence of the partitionless nature of the austenite–ferrite transformation, followed by partitioning of carbon into the residual austenite and the subsequent exhaustion of the chemical driving force for the (partitionless) face-centered cubic (fcc) → body-centered cubic (bcc) phase transformation.

A prediction that follows from Bhadeshia's argument is a definite limit in the carbon enrichment of the remaining austenite during bainitic transformation. In fact, using thermodynamic arguments, it is suggested that one must take the elastic energy barrier for the growth of bainite plates into account. Bhadeshia estimated the barrier to be about $\sim 400 \text{ J mol}^{-1}$ between austenite and ferrite [13]. This extra energy barrier leads to a further constraint in the maximum carbon enrichment in austenite, and the locus of this composition at different BIT temperatures is usually denoted as T'_0 . Beyond this critical enrichment, the transformation cannot continue. From comparisons between experiments and thermodynamic models, because of the non-homogeneous C-distribution, Chang and Bhadeshia [14] also proposed that the maximum carbon enrichment of austenite during BIT occurs when the carbon composition of austenite reaches the so-called T_0 point, at which the Gibbs energies of ferrite and austenite are equal. Over the past few decades, many experiments have actually shown that the level of enrichment of carbon in austenite at the end of the (incomplete) BIT tends to be close to the T_0 or T'_0 curves (see e.g. Ref. [11]).

Moreover, very recent atom probe tomography experiments by Caballero et al. [15–18] on so-called “slow bainite” show that bainitic ferrite is indeed supersaturated with carbon – or at least has a much higher C concentration than would be expected if the bainite transformation occurred through diffusional processes – at the early stages of the transformation, providing further support for the displacive (partitionless) nature of bainitic transformation, at least in ultraslow bainite. It is reported that after 1273 K/15 min and 473 K/240 h the carbon content is as high as 8–12 at.% (when wt.% is about 1.8–2.8), which is a composition that lies between T'_0 and paraequilibrium Ae_3 as the austenite film thickness (t_A) is about 10–50 nm; when t_A is larger than 50 nm, the carbon content is about 5–8 at.% (about 1.1–1.8 wt.%) [19]. These works indicate that, within the thicker austenite film, the carbon content is closer to $w_C^{T'_0}$. In the present work, the analysis of the BIT process assumes that the transformation is partitionless and that the thermodynamic arguments for the interruption of BIT (i. e. T'_0 curve) are valid.

1.3. Motivation for this work

As mentioned above, the fact that the driving force for bainitic transformation can be exhausted at some point

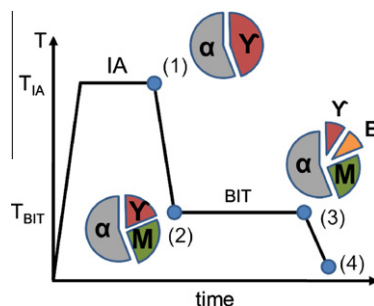


Fig. 1. Schematic of the two-step heat treatment in TRIP-assisted steels. IA: inter-critical annealing; BIT: bainite isothermal transformation; α : ferrite; γ : austenite; M: martensite; B: bainitic ferrite.

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